I_d-I_q Control strategy for mitigation of Current harmonics with PI Controller using Simulation and RTDS Hardware

Suresh Mikkili and A.K. Panda

Department of Electrical Engineering, N.I.T Rourkela

msuresh.ee@gmail.com and akpanda.ee@gmail.com

Abstract: - *This paper presents a control strategy for a three phase four-wire shunt active power filter (SAPF). The shunt active filter is a custom-power device capable to compensate, in real time, harmonics and unbalances in an electrical system. The main objective of this paper is to analyse the performance of instantaneous real active and reactive current (i_d-i_q) control strategy for extracting reference currents of shunt active filters under balanced, un-balanced and balanced non-sinusoidal conditions with **PI controller** in MATLAB/Simulink environment and also with Real Time Digital Simulator (RTDS Hardware). When the supply voltages are balanced and sinusoidal, the all control strategies are converge to the same compensation characteristics; However, the supply voltages are distorted and/or un-balanced sinusoidal, these control strategies result in different degrees of compensation in harmonics. The compensation capabilities are not equivalent, with p-q control strategy unable to yield an adequate solution when source voltages are not ideal. Extensive simulations are carried out with PI controller for I_d-I_q control strategy under different main voltages. The 3-ph 4-wire SHAF system is also implemented on RTDS Hardware to further verify its effectiveness. The detailed simulation and RTDS Hardware results are included.*

Index Terms— *Harmonic compensation, SAPF, i_d-i_q control strategy, PI Controller and RTDS Hardware.*

1. INTRODUCTION

When a pure sinusoidal voltage is applied to a certain type of load, the current drawn by the load is proportional to the voltage and impedance and follows the envelope of the voltage waveform. These loads are referred to as linear loads (loads where the voltage and current follow one another without any distortion to their pure sine waves). Examples of linear loads are resistive heaters, incandescent lamps, and constant speed induction and synchronous motors.

In contrast, some loads cause the current to vary disproportionately with the voltage during each half cycle, These loads are defined as nonlinear loads, and the current and voltage have waveforms that are no sinusoidal, containing distortions, whereby the 50-Hz waveform has numerous additional waveforms superimposed upon it, creating multiple frequencies within the normal 50-Hz sine wave. The multiple frequencies are harmonics of the fundamental frequency. Examples of nonlinear loads are battery chargers, electronic ballasts, variable frequency drives, and switching mode power supplies [1-3]. As nonlinear currents flow through a facility's electrical system and the distribution-transmission lines, additional voltage distortions are produced due to the impedance associated with the electrical network. Thus, as electrical power is generated, distributed, and utilized, voltage and current waveform distortions are produced. It is noted that non-sinusoidal current results in many problems for the utility power supply company, such as: low power factor, low energy efficiency, electromagnetic interference (EMI), distortion of line voltage etc.

Eminent issues always arises in three-phase four-wire system, it is well-known that zero line may be overheated or causes fire disaster as a result of excessive harmonic current [4] going through the zero line three times or times that of three. Thus a perfect compensator is necessary to avoid the consequences due to harmonics. Though several control techniques and strategies had developed but still performance of filter in contradictions, these became primarily motivation for the current paper.

Present paper mainly focused on instantaneous active and reactive currents (i_d–i_q) control strategy, which is prominent one with this we analysed the performance of filter under different main voltages with PI controller. To validate current observations, Extensive simulations were performed and adequate results were presented. The 3-ph 4-wire SHAF system is also implemented on a Real Time Digital Simulator (RTDS Hardware) to further verify its effectiveness.

2. SHUNT ACTIVE FILTER

The active filter currents are achieved from the instantaneous active and reactive powers *p* and *q* of the non-linear load [5-6]. Fig.1 shows a basic architecture of three-phase - four wire shunt active filter.
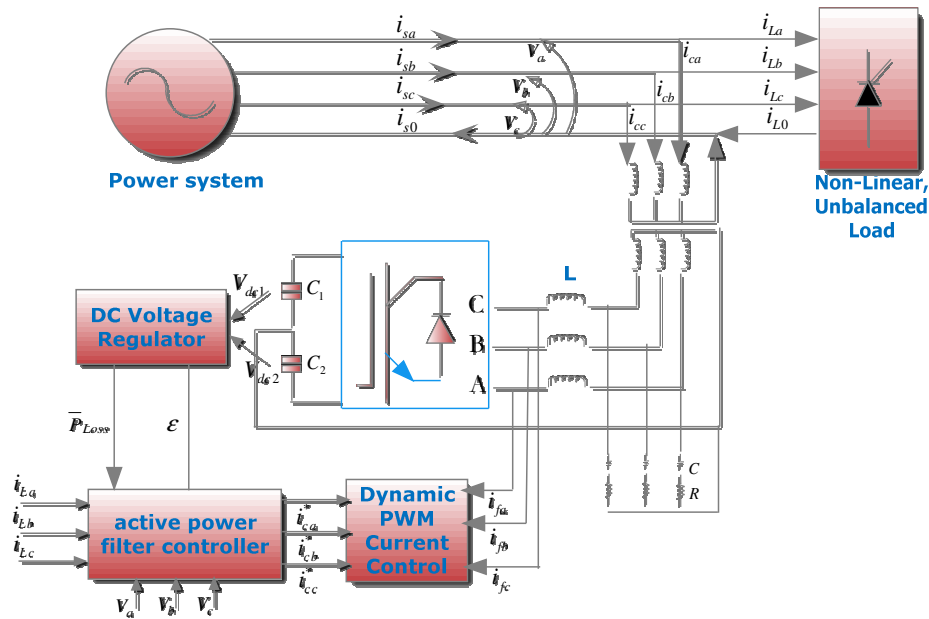
Fig.1. Basic architecture of three-phase - four wire shunt active filter.

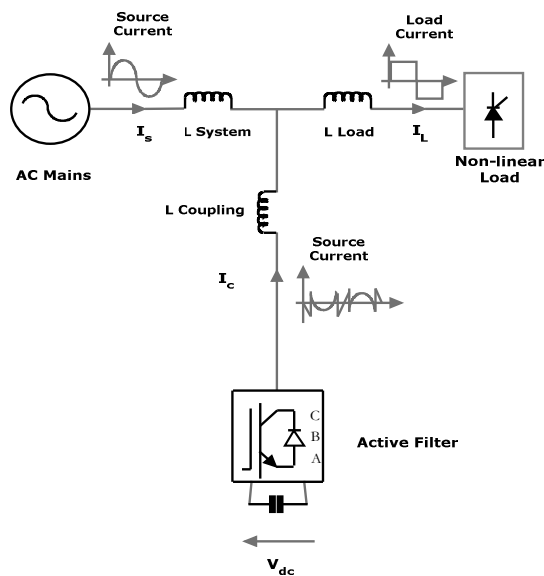## 2.1 Compensation principle: -

Fig 2. Compensation Characteristics of a Shunt Active power filter

The active power filter is controlled to draw/supply the a compensating current if from/to the load to cancel out the current harmonics on AC side and reactive power flow from/to the source there by making the source current in phase with source voltage. Figure 2 shows the basic compensation principle of the active power filter.

2.2 Instantaneous active and reactive current method (i_d – i_q):

In this method reference currents are obtained through instantaneous active and reactive currents i_d and i_q [7-8] of the non linear load. Calculations follows Similar to the instantaneous power theory, however dq load currents can be obtained from equation (1). Two stage transformations give away relation between the stationary and rotating reference frame with active and reactive current method. Fig.4 shows voltage and current vectors in stationary and rotating reference frames. The transformation angle 'θ' is sensible to all voltage harmonics and unbalanced voltages; as a result $d\theta/dt$ may not be constant.

The reference frame d-q (d direct axis, q-quadrature axis) is determined by the angle θ with respect to the α-β frame used in the p-q theory. The transformation from α – β – 0 frame to d–q –0 frame is given by

$$
\begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} = \frac{1}{v_{\alpha\beta}} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (1)
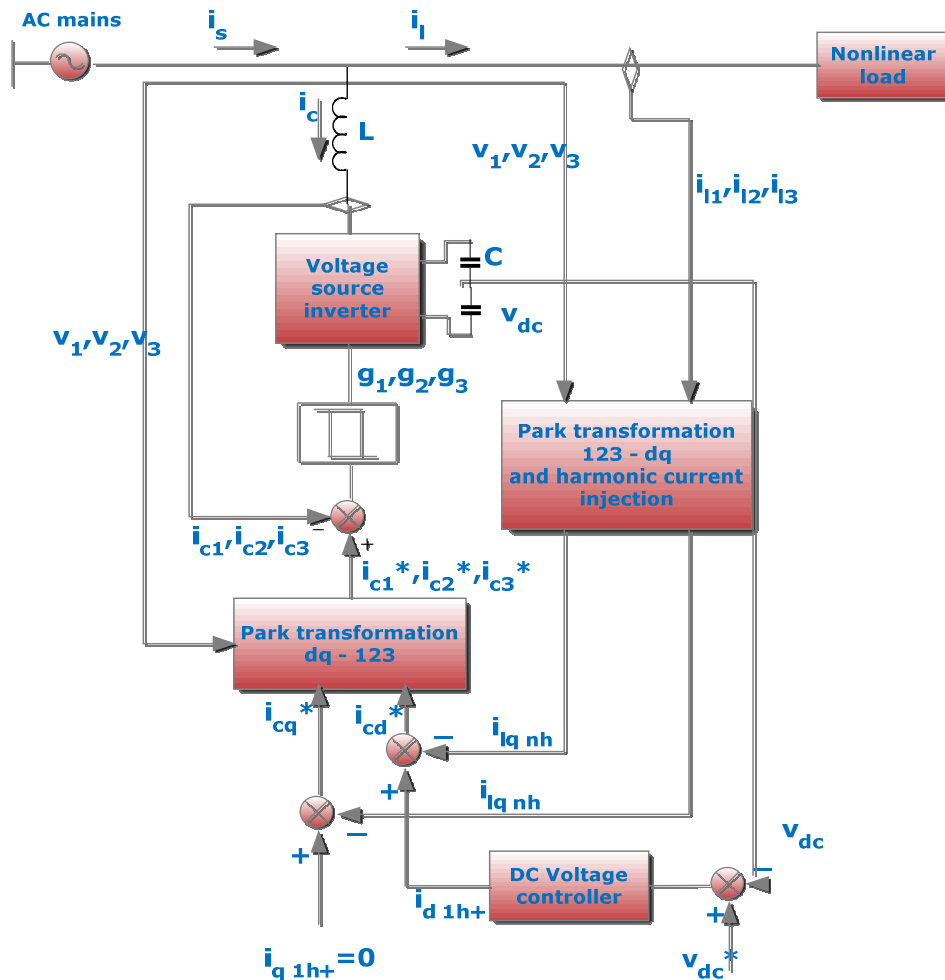$$

If the d axis is in the direction of the voltage space vector, since the zero-sequence component is invariant, the transformation is given by

$$
\begin{bmatrix} i_d \\ i_q \end{bmatrix} = S \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (2)
$$

$$
S = \frac{1}{v_{\alpha\beta}} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \quad (3)
$$

$$S = \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \qquad (4)$$

Where the transformation matrix S, satisfies $\|S\| = 1$ and $S^{-1} = S^T$

Each current component (i_d, I_q) has an average value or dc component and an oscillating value or ac component

$$i_d = \overline{i_d} + \widetilde{i_d}$$
$$i_q = \overline{i_q} + \widetilde{i_q} \qquad (5)$$

Fig.3. Active powers filter control circuit.

The compensating strategy (for harmonic reduction and reactive power compensation) assumes that the source must only deliver the mean value of the direct-axis component of the load current. The reference source current will therefore be

$$i_{sdref} = \overline{i_{Ld}} \quad ; \quad i_{sqref} = i_{s0ref} = 0 \qquad (6)$$

In this method, only the currents magnitudes are transformed and p-q formulation is only performed on the instantaneous active i_d and instantaneous reactive i_q components.

If the d axis has the same direction as the voltage space vector $\overline{v}$, then the zero-sequence component of current remains invariant. Therefore, the i_d - i_q method may be expressed as follows:

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{1}{v_{\alpha\beta}} \begin{bmatrix} v_\alpha & v_\beta & 0 \\ -v_\beta & v_\alpha & 0 \\ 0 & 0 & v_{\alpha\beta} \end{bmatrix} \begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \\ i_{L0} \end{bmatrix} \qquad (7)$$

In this strategy, the source must deliver the constant term of the direct-axis component of load (for harmonic compensation and power factor correction). The reference source current will be calculated as follows:

$$i_{sd} = \overline{i_{Ld}} \quad ; \quad i_{sq} = i_{so} = 0 \qquad (8)$$

$$i_{Ld} = \frac{v_\alpha i_{L\alpha} + v_\beta i_{L\beta}}{v_{\alpha\beta}} = \frac{P_{L\alpha\beta}}{\sqrt{v_\alpha^2 + v_\beta^2}} \qquad (9)$$

The dc component of the above equation will be

$$\overline{i_{Ld}} = \left(\frac{P_{L\alpha\beta}}{v_{\alpha\beta}}\right)_{dc} = \left(\frac{P_{L\alpha\beta}}{\sqrt{v_\alpha^2 + v_\beta^2}}\right)_{dc} \qquad (10)$$

Where the subscript "dc" means the average value of the expression within the parentheses.

Since the reference source current must to be in phase with the voltage at the PCC (and have no zero-sequence component), it will be calculated (in α-β-0 coordinate) by multiplying the above equation by a unit vector in the direction of the PCC voltage space vector (excluding the zero-sequence component):

$$i_{sref} = \overline{i_{Ld}} \frac{1}{v_{\alpha\beta}} \begin{bmatrix} v_\alpha \\ v_\beta \\ 0 \end{bmatrix} \qquad (11)$$

$$\begin{bmatrix} i_{s\alpha ref} \\ i_{s\beta ref} \\ i_{s0ref} \end{bmatrix} = \left(\frac{P_{L\alpha\beta}}{v_{\alpha\beta}}\right)_{dc} \frac{1}{v_{\alpha\beta}} \begin{bmatrix} v_\alpha \\ v_\beta \\ 0 \end{bmatrix} \qquad (12)$$

Fig.3 and 5 show the control diagram for shunt active filter and harmonic injection circuit. On

owing load currents i_d and i_q are obtained from park transformation then they are allowed to pass through the high pass filter to eliminate dc components in the nonlinear load currents. Filters used in the circuit are Butterworth type and to reduce the influence of high pass filter an alternative high pass filter (AHPF) can be used in the circuit. It can be obtained through the low pass filter (LPF) of same order and cut-off frequency simply difference between the input signal and the filtered one, which is clearly shown in Fig.5. Butterworth filters used in harmonic injecting circuit have cut-off frequency equal to one half of the main frequency ($f_c=f/2$), with this a small phase shift in harmonics and sufficiently high transient response can be obtained.

$$\begin{bmatrix} i_{s\alpha ref} \\ i_{s\beta ref} \\ i_{s0ref} \end{bmatrix} = \left(\frac{P_{L\alpha\beta}}{\sqrt{v_\alpha^2 + v_\beta^2}}\right)_{dc} \frac{1}{\sqrt{v_\alpha^2 + v_\beta^2}} \begin{bmatrix} v_\alpha \\ v_\beta \\ 0 \end{bmatrix} \qquad (13)$$
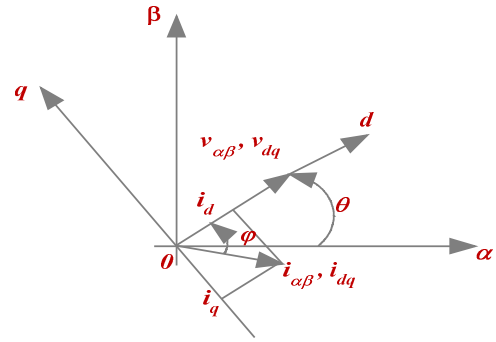

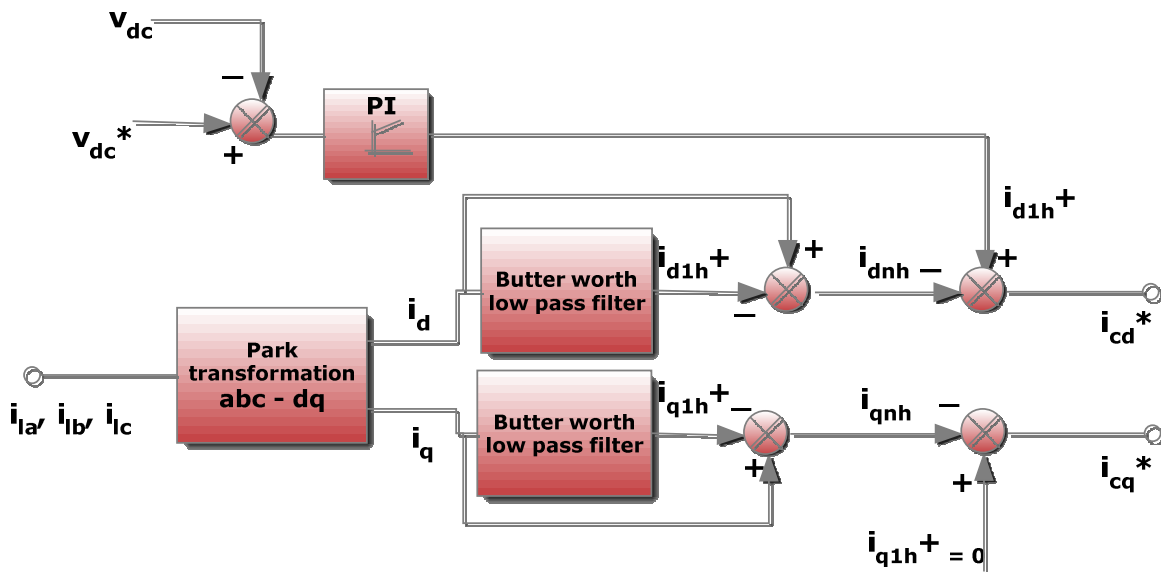**Fig.4.** Instantaneous voltage and current vectors.

Fig. 5. Park transformation and harmonic current injection circuit.

The function of voltage regulator on dc side is performed by proportional – integral (PI) controller, inputs to the PI controller are, change in dc link voltage (V_{dc}) and reference voltage ($V_{dc}*$), on regulation of first harmonic [10] active current of positive sequence i_{d1h}^+ it is possible to control the active power flow in the VSI and thus the capacitor voltage V_{dc}. In similar fashion reactive power flow is controlled by first harmonic reactive current of positive sequence i_{q1h}^+. On the contrary the primary end of the active power filters is just the exclusion of the harmonics caused by nonlinear loads hence the current i_{q1h}^+ is always set to zero.

3. CONSTRUCTION OF PI CONTROLLER

Fig.6 shows the internal structure of the control circuit. The control scheme consists of PI controller, limiter, and three phase sine wave generator for reference current generation and generation of switching signals. The peak value of reference currents is estimated by regulating the DC link voltage. The actual capacitor voltage is compared with a set reference value [11].
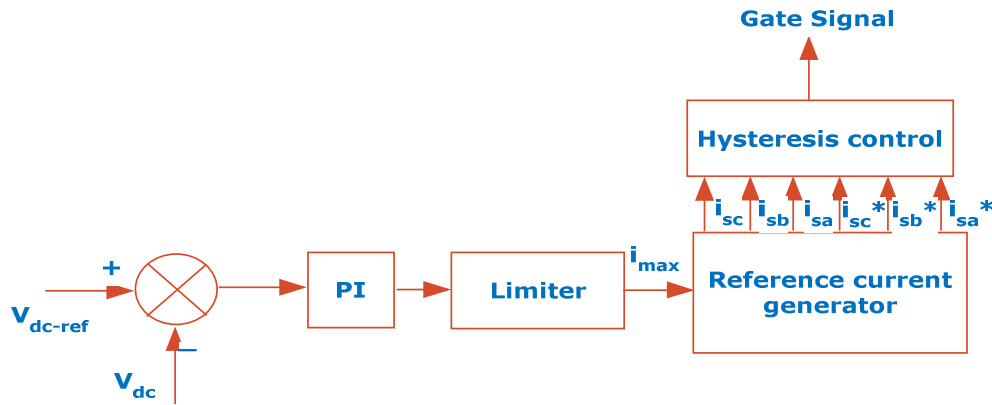

Fig.6 Conventional PI Controller

The error signal is then processed through a PI controller, which contributes to zero steady error in tracking the reference current signal. The output of the PI controller is considered as peak value of the supply current (I_{max}), which is composed of two components: (a) fundamental active power component of load current, and (b) loss component of APF; to maintain the average capacitor voltage to a constant value. Peak value of the current (I_{max}) so obtained, is multiplied by the unit sine vectors in phase with the respective source voltages to obtain the reference compensating currents. These estimated reference currents ($I_{sa}*$, $I_{sb}*$, $I_{sc}*$) and sensed actual currents (Isa, Isb, Isc) are compared at a hysteresis band, which gives the error signal for the modulation technique. This error signal decides the operation of the converter switches. In this current control circuit configuration, the source/supply currents I_{sabc} are made to follow the sinusoidal reference current I_{abc}, within a fixed hysteretic band. The width of hysteresis window determines the source current pattern, its harmonic spectrum and the switching frequency of the devices. The DC link capacitor voltage is kept constant throughout the operating range of the converter. In this scheme, each phase of the converter is controlled independently. To increase the current of a particular phase, the lower switch of the converter associated with that particular phase is turned on while to decrease the current the upper switch of the respective converter phase is

turned on. With this one can realize, potential and feasibility of PI controller.

4. RTDS HARDWARE

The Real Time Digital Simulator (RTDS) allows developers to accurately and efficiently simulate electrical power systems and their ideas to improve them The RTDS Simulator [12-14] operates in real time, therefore not only allowing the simulation of the power system, but also making it possible to test physical protection and control equipment. This gives developers the means to prove their ideas, prototypes and final products in a realistic environment.

The RTDS is a fully digital power system simulator capable of continuous real time operation. It performs electromagnetic transient power system simulations with a typical time step of 50 microseconds utilizing a combination of custom software and hardware. The proprietary operating system used by the RTDS guarantees "hard real time" during all simulations. It is an ideal tool for the design, development and testing of power system protection and control schemes. With a large capacity for both digital and analogue signal exchange (through numerous dedicated, high speed I/O ports) physical protection and control devices are connected to the simulator to interact with the simulated power system.

4.1 Simulator Hardware

The real time digital simulation hardware used in the implementation of the RTDS is modular, hence making it possible to size the processing power to the simulation tasks at hand. Figure 7 illustrates typical hardware configurations for real time digital simulation equipment. As can be seen, the simulator can take on several forms including a new portable version which can easily be transported to a power-plant or substation for on-site pre-commissioning tests. Each rack of simulation hardware contains both processing and communication modules. The mathematical computations for individual power system components and for network equations are performed using one of two different processor modules. An important aspect in the design and implementation of any real time simulation [15] tool is its ability to adapt to future developments. Since the power system industry itself continues to advance with the introduction new innovative devices, both the hardware and software of the simulator must be able to follow such changes. Great care has been taken to ensure such upward compatibility in all aspects of the real time simulator. Adhering to this approach provides significant benefit to all simulator users since they are able to introduce new features to already existing simulator installations.

The present real-time electric simulator is based on RT LAB real-time, distributed simulation platform; it is optimized to run Simulink in real-time, with efficient fixed-step solvers, on PC Cluster. Based on COTS non-proprietary PC components, RT LAB is a modular real-time simulation platform, for the automatic implementation of system-level, block diagram models, on standard PC's. It uses the popular MATLAB/Simulink as a front-end for editing and viewing graphic models in block-diagram format. The block diagram models become the source from which code can be automatically generated, manipulated and downloaded onto target processors (Pentium and Pentium-compatible) for real-time or distributed simulation.

Fig.7 RTDS Hardware

5. SYSTEM PERFORMANCE

In this section 3 phase 4 wire shunt active power filter responses are presented in transient and steady state conditions. In the present simulation AHPF (alternative high pass filter) were used in Butterworth filter with cut-off frequency $f_c = f/2$. Simulation shown here are for different voltage conditions like sinusoidal, non-sinusoidal, unbalanced, and with different main frequencies. Simulation is carried out for instantaneous active and reactive current theory (i_d- i_q) with PI controller.

Fig.8, Fig.9 and Fig.10 illustrates the performance of shunt active power filter under different main voltages, as load is highly inductive, current draw by load is integrated with rich harmonics.

Fig.7 illustrates the performance of Shunt active power filter under balanced sinusoidal voltage condition, THD for i_d-i_q method with PI Controller using Matlab simulation is 1.97% and using RT DS Hard ware is 2.04% . Fig.8 illustrates the performance of Shunt active power filter under un-balanced sinusoidal voltage condition, THD for i_d-i_q method with PI Controller using Matlab

simulation is 3.11% and using RT DS Hard ware is 3.26%. Fig.9 illustrates the performance of Shunt active power filter under balanced non-sinusoidal voltage condition, THD for i_d-i_q method with PI Controller using Matlab simulation is 4.92% and

using RT DS Hard ware is 5.05%. By using Instantaneous active and reactive current theory with PI controller, the system performance is quite good not only under balanced condition but also under un-balanced and non-sinusoidal conditions.
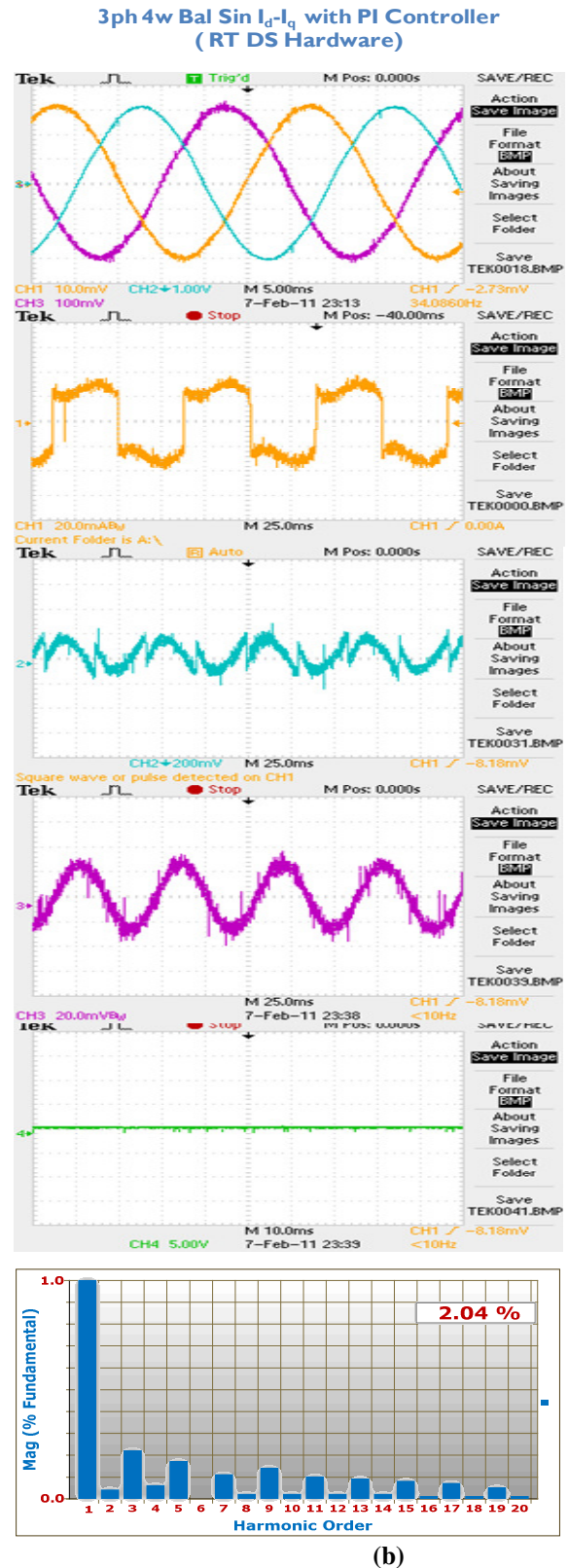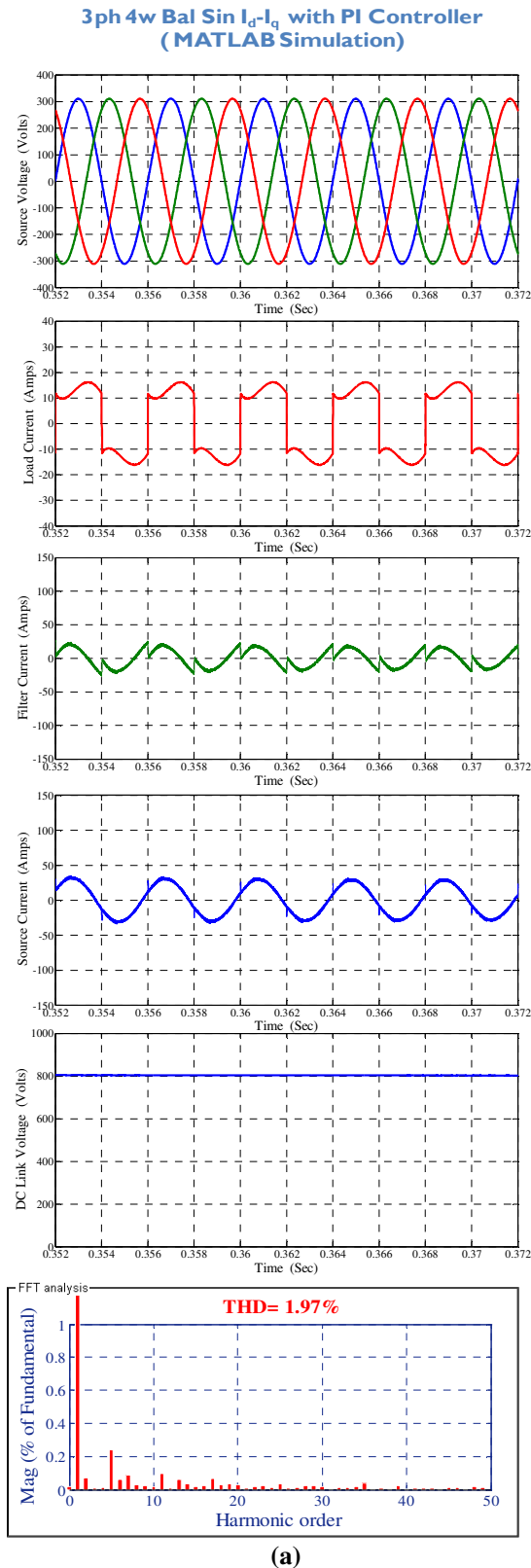

Fig 8. Shunt ative filter response using I_d-I_q Control Strategy PI controller Under Balanced Sinusoidal
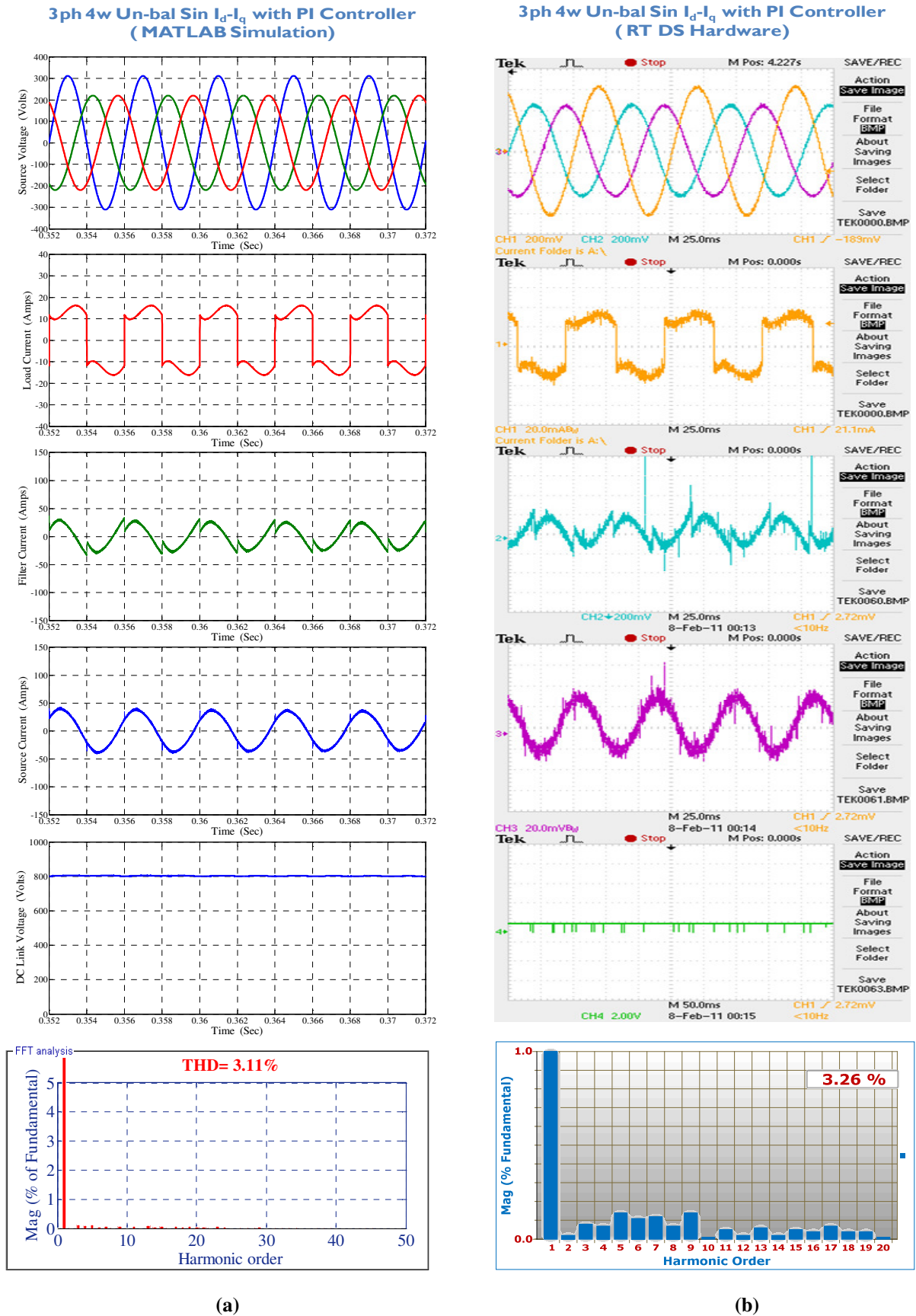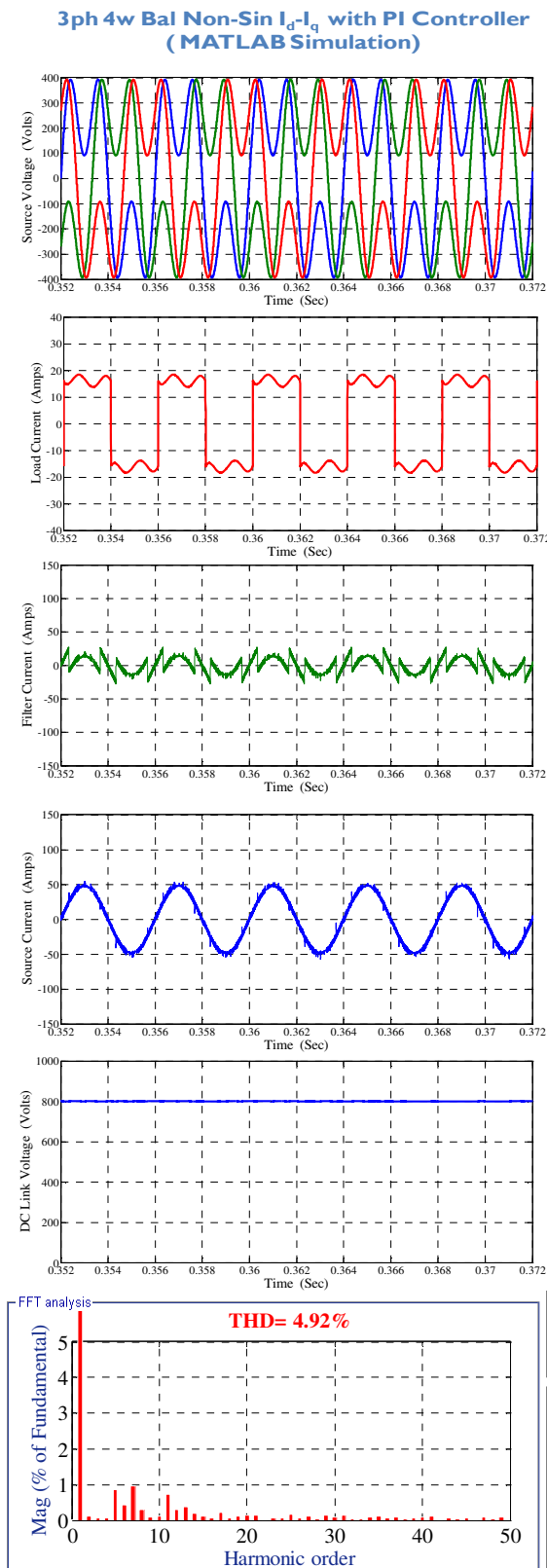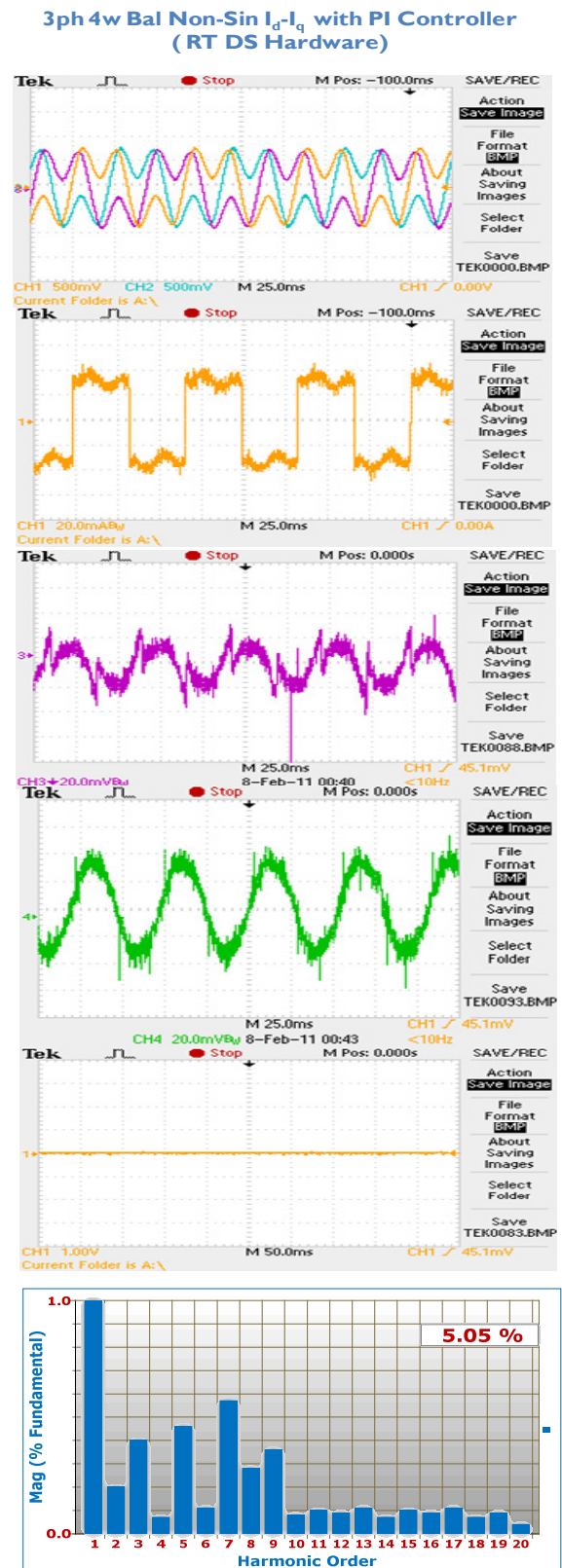(a) Matlab Simulation (b) RT DS Hardware

Fig 9. Shunt ative filter response using I_d-I_q Control Strategy PI controller Under Un-balanced Sinusoidal

(a) Matlab Simulation (b) RT DS Hardware

3ph 4w Bal Non-Sin I_d-I_q with PI Controller (MATLAB Simulation)

3ph 4w Bal Non-Sin I_d-I_q with PI Controller (RT DS Hardware)

(**a**)   (**b**)

Fig 10. Shunt ative filter response using I_d-I_q Control Strategy PI controller Under Balanced Non-Sinusoidal

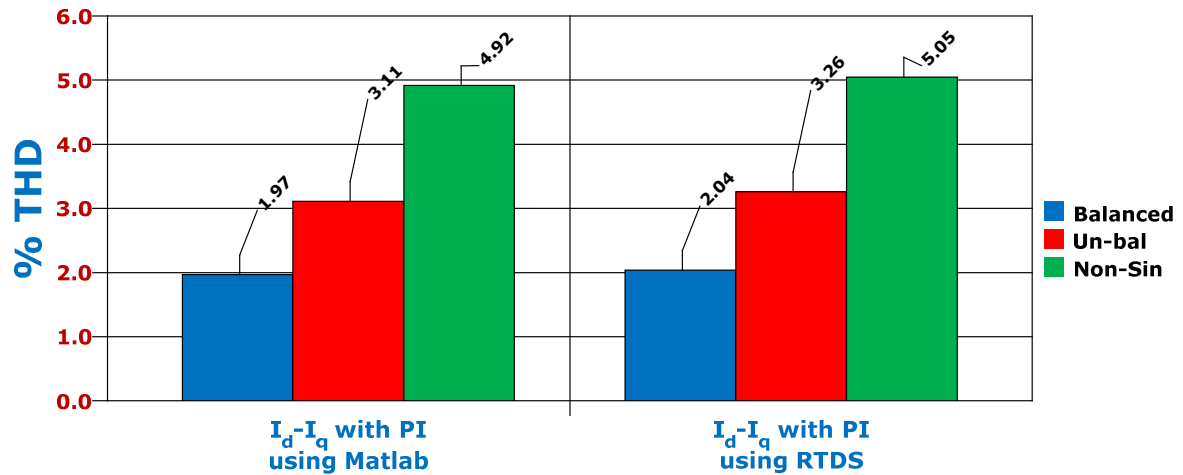(a)   Matlab Simulation   (b) RT DS Hardware

Fig. 11 THD for id-iq method using Matlab and RTDS Hardware

6. CONCLUSION

In the present paper instantaneous active and Reactive current control strategy with PI controller is developed and verified with three phase four wire system in Matlab/simulink environment and also using Real Time Digital Simulator. This control strategy is capable to suppress the harmonics in the system during balanced sinusoidal, un-balanced sinusoidal and balanced non-sinusoidal conditions. The compensation capabilities are not equivalent, with p-q control strategy unable to yield an adequate solution when source voltages are not ideal. *p-q* theory needs additional PLL circuit for synchronization so *p-q* method is frequency variant, where as in i_d-i_q method angle 'θ' is calculated directly from main voltages and thus enables the method to be frequency independent. Thus large numbers of synchronization problems with un-balanced and non-sinusoidal voltages are also avoided. Addition to that DC voltage regulation system valid to be a stable and steady-state error free system was obtained. Overall the system performance is quite good not only under balanced condition but also under un-balanced and non-sinusoidal condition using i_d-i_q control strategy with PI controller.

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